EUROPHYSICS LETTERS

Europhys. Lett., (), pp. ()

Current flow past an etched barrier: field emission from a two-dimensional electron gas

D. H. Cobden[1], G. Pilling[1], R. Parthasarathy[1], P. L. McEuen[1], I. M. Castleton[2], E. H. Linfield[2], D. A. Ritchie[2], and G. A. C. Jones[2]

[1] *Department of Physics, University of California and Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[2] *Cavendish Laboratory, Madingley Road, Cambridge, CB3 OHE, UK*

(received ; accepted)

PACS. 73.40Kp – III-V semiconductor-to-semiconductor contacts, p-n junctions, and hetero-junctions.
PACS. 79.70.+q– Field emission, ionization, evaporation, and desorption.

Abstract. – We find that, under appropriate conditions, electrons can pass a barrier etched across a two dimensional electron gas (2DEG) by field emission from the GaAs/AlGaAs hetero-junction into a second, low-density 2DEG formed deep in the substrate. The current-voltage characteristics exhibit a rapid increase in the current at the field emission threshold and intrinsic bistability above this threshold, consistent with a heating instability occurring in the second 2DEG. These results may explain similar behaviour recently seen in a number of front-gated devices by several groups.

Extensive studies of two-dimensional electron systems over the last two decades have relied on the ability to trap electrons at an interface between two materials with different band energies. Most popular amongst these systems is the high-mobility GaAs/Al$_x$Ga$_{1-x}$As heterojunction [1]. Here the electrons are confined principally by attraction to remote donors placed in the AlGaAs. However, in order for there to be complete confinement there must also exist an electric field in the GaAs substrate pushing the electrons towards the heterojunction. In practice, this substrate field is typically provided by negative charge on residual acceptors in the substrate and surface boundary conditions [2]. A very interesting situation arises if this confinement field vanishes. The electrons are then predicted to be very weakly bound at the interface, by the work function of the 2DEG, as discussed by Groshev and Schoen [3]. The work function depends sensitively on the density of the 2DEG and is strongly influenced by many-body effects such as the image potential. Because of the weak confinement, field emission of electrons into the substrate may be anticipated in a weak electric field applied perpendicular to the interface.

In this letter we discuss a simple device that demonstrates the field emission of electrons from a 2DEG. We find that a current can flow past an etched barrier in a 2DEG if the

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substrate field is adjusted using a positive voltage applied to a back gate. The electrons are field emitted from the 2DEG and travel underneath the etched barrier. The magnetic field dependence demonstrates that the current is carried via a low-density 2DEG formed at an upside-down heterojunction below the uppermost GaAs substrate layer. The observed current-voltage characteristics in this regime are highly nonlinear. Above a threshold bias the current rises rapidly and exhibits bistability. We show that this bistability results from thermal runaway due to heating of the (initially localized) electrons in lower 2DEG by the field-emitted electrons from the upper 2DEG.

These results are important for three reasons. First, they demonstrate a simple geometry in which the process of field emission from a 2DEG can be studied. Second, they illustrate the existence of a thermal instability in an initially insulating, low-density 2DEG. Finally, they offer insight into a number of recent experiments on transport across a lateral barrier [4, 5, 6, 7] on a GaAs/AlGaAs heterostructure. The latter experiments all revealed very similar behaviour to that reported here. Various explanations were put forward, including the heating of an accidental puddle of electrons within the barrier [5], impurities exchanging electrons [6], and interplay with gate leakage current [8]. In many of these cases, however, the bistability occured under conditions when the substrate field vanished (after illumination), indicating that the mechanism proposed here may explain these experiments as well.

The device geometry, heterostructure composition and measurement configuration are indicated in fig. 1(a). The back gate is a 50 nm layer of n+ GaAs which is contacted separately from the 2DEG using *in situ* ion-beam patterning (see ref. [9]). Above this is a 500 nm AlGaAs barrier, followed by 500 nm of GaAs at the top of which is the normal heterojunction. At $V_g = 0$, a 2DEG of density 2.5×10^{11} cm^{-2} and mobility 3.0×10^5 cm^{2}V^{-1}s^{-1} resides at this heterojunction. The barriers in the 2DEG are produced by electron-beam lithography and wet etching on the arms of a Hall-bar mesa. The etch width ($\sim$ 200 nm) and depth ($\sim$ 50 nm) create a potential barrier at the heterojunction that is known to be hundreds of millivolts high [10]; enough to make the barriers completely insulating at both room and low temperature [11].

Fig. 1(b) shows the I-V characteristics of a barrier at temperature $T = 4.2$ K for different gate voltages V_g. A bias V of up to 100 mV is applied to one contact, and the current I is measured with a virtual-earth current preamplifier attached to the other contact. As V_g is increased from zero, I is zero until $V_g = 1.53$ V. Then, up to $V_g \gg 1.60$ V, I remains zero at low V but grows rapidly above a threshold bias. Near this threshold there is bistability between a low- and a high-current state, causing hysteresis between up and down sweep directions (indicated by arrows at $V_g = 1.54$ V) [12]. The threshold bias (the value of V at which I in the high-current state extrapolates to zero) decreases towards a limiting value $V_{lim} \approx 40$ mV as V_g is increased. At $V_g \gg 1.60$ V the bistability disappears and simultaneously the conductance at $V = 0$ becomes finite. Measurements on a number of barriers revealed very similar characteristics.

To understand these results, we first consider the effect of V_g on the unetched 2DEG. The solid line in fig. 2(a) is the density, n_1, of the 2DEG deduced from the low-field Hall coefficient of an unetched region, while the filled circles here are the values of n_1 obtained from Shubnikov-de Haas oscillations. We see that n_1 increases linearly with V_g up to about 1.4 V, above which it levels off at 3.5×10^{11} cm^{-2}. The reason for this levelling off [9] is the population of a second 2DEG, as is illustrated by the band diagrams in fig. 3. At $V_g = 0$ the lower heterojunction, at the bottom of the 500 nm GaAs layer, is far above E_F and the electrons are tightly confined by the electric field in the GaAs to the upper heterojunction. The linear increase in n_1 for $V_g < 1.4$ V is determined by the capacitance between the upper heterojunction and the back gate, whose separation is 1020 nm. At $V_g = 1.4$ V the lower

heterojunction reaches the Fermi level E_F and a second 2DEG forms there. For $V_g > 1.4$ V, the band in the GaAs remains almost flat, and n_1 remains constant. The density n_2 in the lower 2DEG then increases according to the dashed line.

Now we examine the properties of the barrier over the same range of V_g. Fig. 2(b) shows the differential conductance, $\frac{\mathrm{d}I}{\mathrm{d}V}$, at $V = 0$ and 100 mV. Both become finite only for $V_g \geq 1.5$ V. The inset shows the variation with magnetic field B of $\frac{\mathrm{d}V}{\mathrm{d}I} \equiv (\frac{\mathrm{d}I}{\mathrm{d}V})^{-1}$, at $V = 100$ mV and $V_g = 1.72$ V. It is roughly linear for $B \geq 0.5$ T, suggestive of a Hall resistance. The same is true at other values of V_g. If at each V_g we interpret the slope as a Hall coefficient, $R_H = \frac{\mathrm{d}(\frac{\mathrm{d}I}{\mathrm{d}V})}{\mathrm{d}B}$, and convert it to a number density $(eR_H)^{-1}$, we obtain the open circles plotted in fig. 2 (a). The results closely follow the predicted behaviour of n_2.

Armed with our understanding of the behaviour of the upper and lower 2DEGs, we can readily interpret these results. The explanation is sketched in fig. 4(a). The repulsive potential created by the etched surface is smallest at the lower heterojunction, as indicated by the contours. It is therefore clear why the barrier only conducts once the gate voltage is such that the lower heterojunction is populated. The current flows past the barrier along the lower 2DEG. The onset of nonlinear conduction in the I-V curves can also be understood. To get from the upper to the lower 2DEG, the electrons must be field emitted from the upper 2DEG. By analogy with field emission in metals, this happens above a characteristic electric field and hence a well defined source-drain bias.

To understand this in more detail, we need to consider the transfer rate from the upper to the lower 2DEG and the conductance G_2 of the lower 2DEG. We first discuss the variation of G_2 with V_g. For $V_g < 1.4$ V, $n_2 = 0$ and hence $G_2 = 0$. For a range of V_g above this, n_2 is low enough that localization by disorder causes G_2 to be activated, ie, $G_2 \approx G_0 \exp[-E_a/k_B T]$. As n_2 increases, the high-T conductance G_0 should increase while the activation energy E_a decreases until at some point G_2 becomes measurable at 4.2 K. It is reasonable that this happens at $V_g = 1.6$ V, when $n_2 \sim 3 \times 10^{10}$ cm^{-2}. In support of this we find from additional measurements that the linear-response barrier conductance is activated, with $E_a = 1.3$ mV and $G_0 = 38$ mS at $V_g = 1.66$ V, and that E_a decreases while G_0 increases with increasing V_g. This scenario is confirmed by the observation that the magnetoresistance of the I-V curves accurately reflects the expected Hall effect of the lower 2DEG, whose two-terminal magnetoresistance is dominated by its Hall resistance at high B. In other words, the on-state resistance is dominated by the resistance of the lower 2DEG.

Having understood the role of the lower 2DEG, we can now ask how field emission from the upper 2DEG is related to the nonlinearity and bistability seen in fig. 1(b). As V is increased, the electric field between the upper and lower heterojunctions grows. When the field perpendicular to the 2DEG reaches some value we expect the rate of electron escape from the upper 2DEG on the negative (left) side of the barrier to rise rapidly, by analogy with field emission from a metal cathode. This is indicated in fig. 4(b). Variational calculations of the 2D subband wavefunctions imply that a 2DEG eventually becomes unstable (to field emission) as the substrate potential is lowered [13]. We can check that within our self-consistent simulation the onset of field emission is sudden. We take the situation in fig. 3 with the lower 2DEG occupied, and incorporate a potential drop ΔV across the GaAs well [14]. At $\Delta V = 0$, all the lower-energy wavefunctions are strongly localized to one or the other side of the well. However, as ΔV is increased, at some point the second subband on the left side of the well develops a tail on the right side. The integrated probability in the tail can be approximated by $\exp[(\Delta V - V_{fe})/\delta]$, where V_{fe} and d are constants. Since once this tail forms electrons in the second subband can spill out of the upper 2DEG across the well, we identify V_{fe} with the field emission threshold within the model. Correspondingly, δ is the characteristic bias range over which field emission starts. The value of V_{fe} obtained depends on the acceptor concentration

in the GaAs layer. A concentration of 2.0×10^{11} cm^{-3} gives $V_{fe} = 31$ mV and $\delta = 1.6$ mV. For all acceptor concentrations we find $\delta \ll V_0$, implying that the onset of field emission is indeed sudden.

If field emission only increased the transfer rate across the well, then the current would quickly be limited by G_2 and the I-V curves would simply show a turn-on above a threshold voltage. However, each field-emitted electron delivers an excess energy of up to $e\Delta V$ to the lower 2DEG, where ΔV is the potential difference between the upper and lower 2DEGs in the field emission region. This may be expected to cause the electron temperature T^* in the lower 2DEG to increase, thereby decreasing G_2 and increasing the current. Within such a scenario a bistability arises naturally [15]. We illustrate this by representing the barrier by the simplified equivalent circuit in the inset to fig. 4(c), consisting of a diode of turn-on voltage V_{fe} in series with the activated conductance $G_0 \exp[-E_a/k_B T^*]$. T^* increases monotonically with VI, the power dissipated. Our justification for neglecting the resistance for current returning from the lower to the upper 2DEG is that the hot electrons can easily traverse the well once they have passed the barrier. Such a circuit exhibits an S-shaped bistable region in its I-V characteristic, due to thermal runaway in the lower 2DEG [15]. Fig. 4(c) shows a characteristic generated using a simple proportional relationship, $T^* = \alpha IV$ and reasonable values of the parameters (see figure caption) chosen for similarity to the data at $V_g = 1.55$ V in fig. 1(b).

According to this model, the limiting threshold bias, V_{lim}, defined in the discussion of fig. 1(b), is a measure of the field-emission threshold, V_{fe}. One may therefore estimate the electric field for field emission to be $E_{fe} \sim V_{lim}/d$, where d is the GaAs well width. For this device we get (40 mV)/(0.5 mm) $= 8 \times 10^4$ Vm^{-1}. This is much lower than for 3D metals, where field emission typically occurs at around 10^9 Vm^{-1} [16]. Of particular interest is the situation where there is no doping in the substrate, and the intrinsic work function [3] may be investigated. Our simulations indicate that E_{fe} is around 5×10^3 Vm^{-1} in this limit. Note that the threshold bias should depend on the geometry of the emitter, with a sharper point resulting in a lower threshold. Future work will address these issues.

Finally, we note that escape from a 2DEG can easily occur whenever the potential is nearly flat in the GaAs substrate. In the present devices, this situation is brought about by making V_g sufficiently positive. It is known, however, that illumination with an LED at low temperatures also flattens the bands in the GaAs by neutralizing acceptors deep in the substrate [2]. Indeed, we have previously seen very similar behaviour in etched barriers on standard heterostructures with no back gate, but only after illumination with red light at 4.2 K [4], and we have subsequently found that a voltage applied to the chip carrier has much the same effect on the characteristics as has V_g in the present devices. These standard heterostructures too have an upside-down heterojunction around 1μm below the normal one, at the top of the superlattice buffer. In Refs. [5, 6, 7] infrared illumination was also applied before the nonlinear and bistable behaviour was observed. We therefore believe that the mechanism described here can explain the puzzling behaviour seen in their standard heterostructure devices as well.

In conclusion, we have demonstrated a nonlinear device that relies on the field emission of electrons from a 2DEG trapped at a heterointerface to a second 2DEG beneath it. The device exhibits bistable I-V's associated with a thermal runaway in the second 2DEG due to heating by the field-emitted electrons. This study opens the way for investigations of the work function of 2D metals [3]. Our experiments show that electrons can escape from 2DEGs more easily than is often appreciated, and this may help to explain the frequent occurrence of nonlinear/bistable behaviour in a variety of heterostructure devices.

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We thank Marc Bockrath, Kent McCormick, Alex Hamilton and Karl Brown for help and

discussions. This work was supported by the Office of Naval Research (LBNL authors), the UK EPSRC (IMC and EHL), and Toshiba Cambridge Research Center (DAR).

Fig. 1 - (a) Schematic view of a device, indicating the layer structure and measurement configuration. (b) I-V characteristics at a series of V_g. In each case V was swept up and down once.

Fig. 2 - (a) Areal electron densities vs V_g. The density of the upper 2DEG, n_1, is obtained both from Hall (solid trace) and Shubnikov-de Haas (filled circles) measurements. The dashed line is the predicted density n_2 of the lower 2DEG. (b) Differential conductance vs V_g at $V = 1$ mV and 100 mV. The inset shows an example of the linear variation of $\frac{\mathrm{d}V}{\mathrm{d}I}$ with magnetic field at $V = 100$ mV, from which the density values plotted as open circles in (a) are derived.

Fig. 3. - Self-consistent band profiles in the unetched heterostructure at three values of V_g, separated by 0.5 V offsets for clarity. The electron density, shaded in black, is superimposed. Uniform negative acceptor densities of 2.0×10^{14} cm^{-3} in the GaAs and 6.5×10^{15} cm^{-3} in the AlGaAs were included, the latter being chosen to bring the lower heterojunction to E_F at $V_g = 1.4$ V.

Fig. 4. - Depiction of current flow past an etched barrier. Contours of potential energy are sketched in, the highest being the one closest to the etched surface. (a) At low bias, only equilibrium transfer occurs between upper and lower 2DEGs. (b) At higher bias (negative on the left), electrons can be field emitted from the upper 2DEG near the barrier. (c) Characteristic of the simplified equivalent circuit (inset) taking $V_{fe} = 38$ mV, $G_0 = 2$ mS, $E_a = 2.5$ meV, and $T^* = \alpha IV$ with $\alpha = 2$ K/pW.

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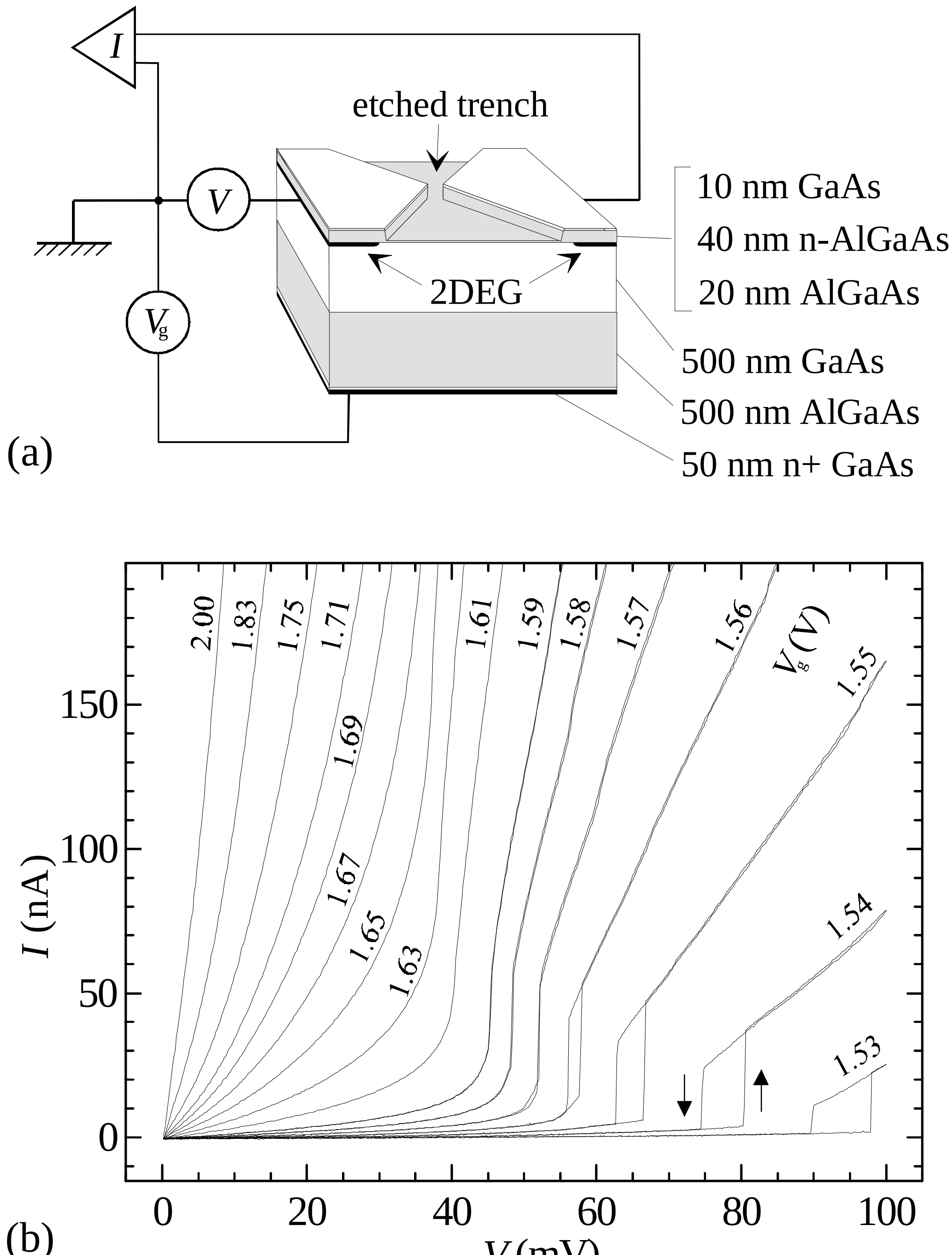
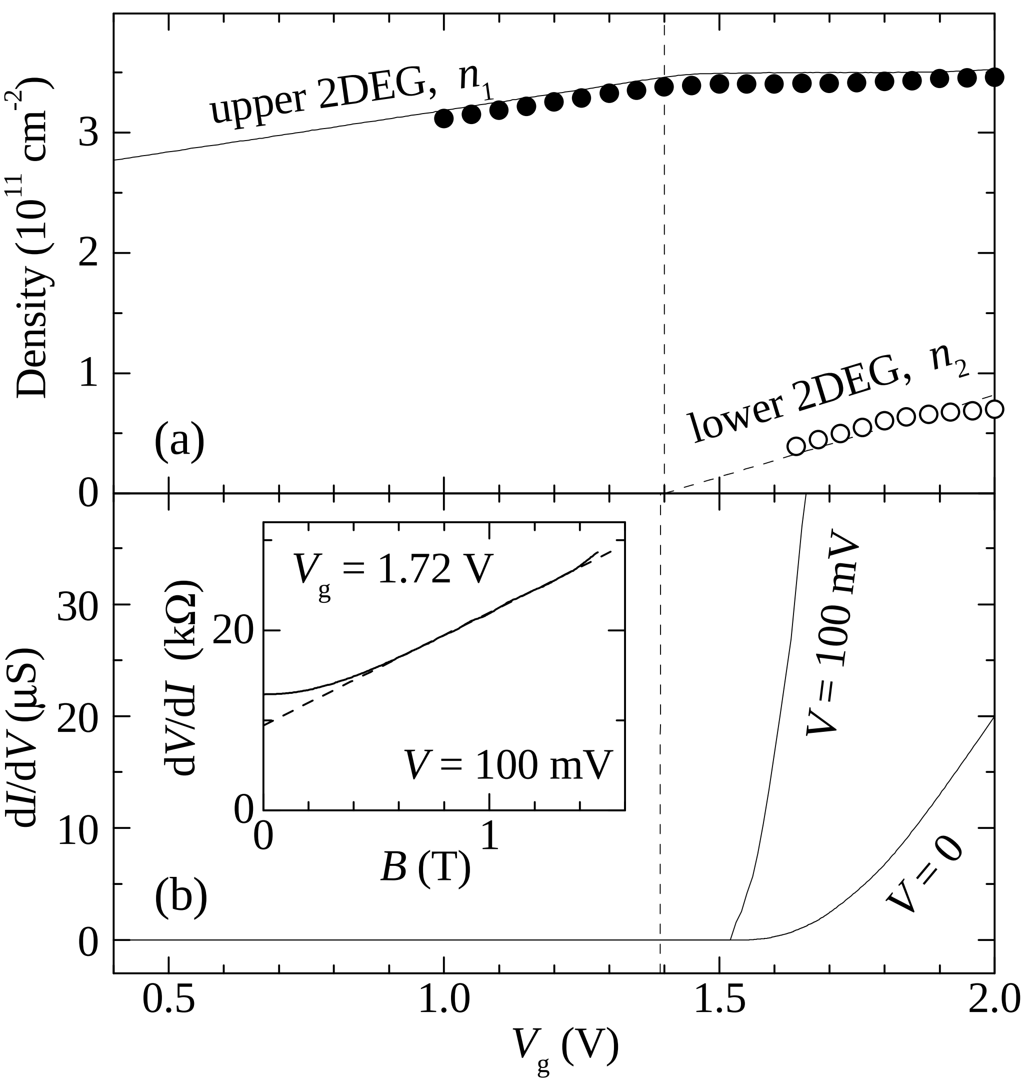
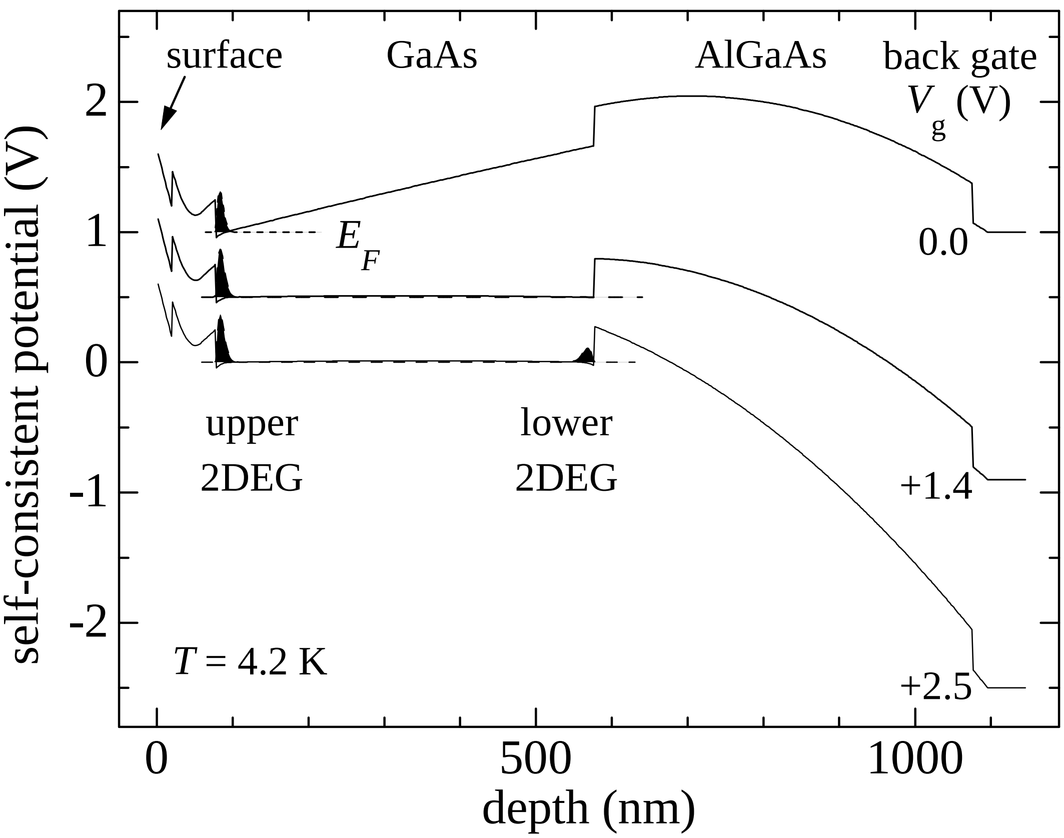
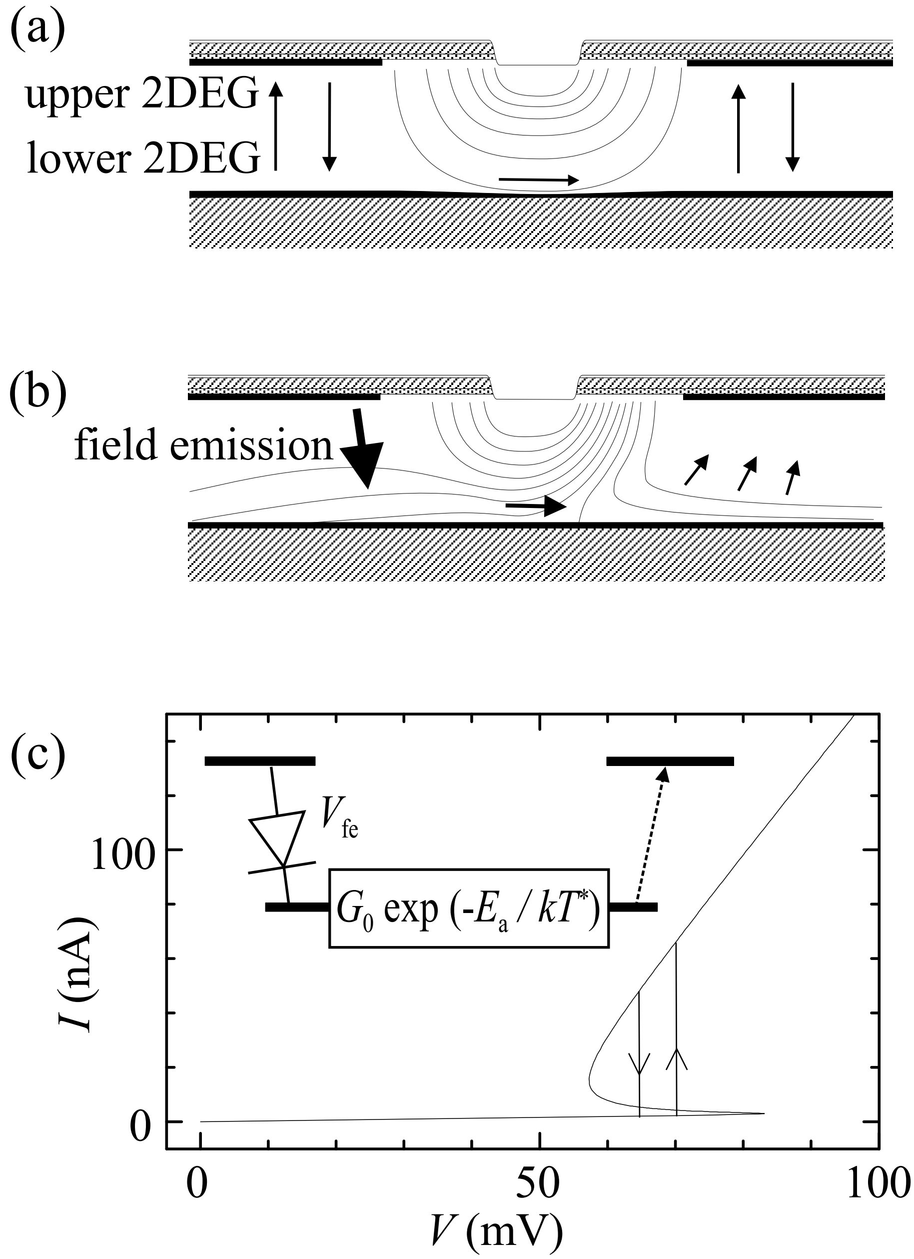


I
etched trench
V
V_g
10 nm GaAs
40 nm n-AlGaAs
20 nm AlGaAs
2DEG
500 nm GaAs
500 nm AlGaAs
50 nm n+ GaAs
(a)
2.00
1.83
1.75
1.71
1.69
1.67
1.65
1.63
1.61
1.59
1.58
1.57
1.56
V_g (V)
1.55
1.54
1.53
I (nA)
150
100
50
0
0
20
40
60
80
100
V (mV)
(b)


upper 2DEG, n_1
lower 2DEG, n_2
Density (10^{11} cm^{-2})
(a)
(b)
dI/dV (µS)
V_g = 1.72 V
dV/dI (kΩ)
V = 100 mV
B (T)
V = 100 mV
V = 0
V_g (V)
0.5
1.0
1.5
2.0


surface
GaAs
AlGaAs
back gate
V_g (V)
E_F
0.0
+1.4
+2.5
upper
2DEG
lower
2DEG
T = 4.2 K
self-consistent potential (V)
depth (nm)
2
1
0
-1
-2
0
500
1000


(a)
upper 2DEG
lower 2DEG
(b)
field emission
(c)
V_{fe}
$G_0 \exp(-E_{\mathrm{a}} / kT^*)$
100
0
I (nA)
0
50
100
V (mV)